RL-TR-97-245
In-House Report
April 1998

OPTICALLY CONTROLLED PHASED ARRAY ANTENNA

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1998	In-House Oct 95 - Dec 96

4. TITLE AND SUBTITLE

OPTICALLY CONTROLLED PHASED ARRAY ANTENNA

5. FUNDING NUMBERS

C - N/A
PE - 62702F
PR - 4600
TA - P1
WU - 23

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory/SNDR
25 Electronic Parkway
Rome NY 13441-4515

8. PERFORMING ORGANIZATION REPORT NUMBER

RL-TR-97-245

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory/SNDR
25 Electronic Parkway
Rome NY 13441-4515

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

RL-TR-97-245

11. SUPPLEMENTARY NOTES

Air Force Research Laboratory Project Engineer: David A. Garafalo/SNDR/(315) 330-3143

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An optically controlled phased array antenna developed by Hughes Aircraft under a DARPA/Rome Laboratory research program was tested at the Rome Laboratory Newport Test Site. The first round of tests were conducted in June/July 1995 and the second round of tests were in May/October 1996. The antenna is a 3-foot by 9 foot phased array capable of a scan angle of 120 degrees. The antenna was designed to be conformal to the cargo door of a large aircraft and is designed to operate in the frequency range of 850 - 1400 MHz with a 50% instantaneous bandwidth. The extensive bandwidth is made possible by the use of photonically based time delays. A typical phased array antenna based on electronic phase shifters would have on the order of a 5% bandwidth. When a bandwidth larger than 5% is attempted with a conventional electronically controlled phased array, beamsquint (or beamwander) will occur. This translates into inaccurate and unreliable radar data. A radar system with the advantage of a 50% bandwidth would make it possible to combine the functions of multiple antennas such as radar, communications and electronic warfare, which collectively operate over a large bandwidth into just one array.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Phased Array Antenna, True Time Delay, Radar, Beamforning	32
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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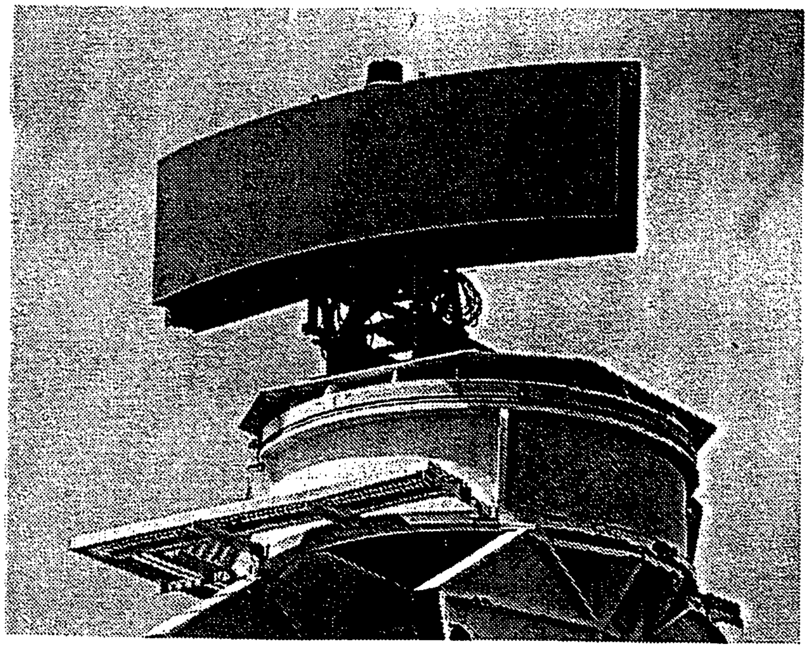

Figure 1. Phased Array Antenna

1. Introduction

An Optically Controlled Phased Array Antenna developed by Hughes Aircraft under an ARPA/Rome Laboratory research program was tested at Rome Labs Newport Test Site. The first round of tests were conducted in June/July 1995 and the second round of tests were in May/October 1996. The antenna is a 3 foot by 9 foot phased array capable of a scan angle of 120 degrees. The antenna was designed to be conformal to the cargo door of a large aircraft and is designed to operate in the frequency range of 850-1400 MHz with a 50% instantaneous bandwidth. The extensive bandwidth is made possible by the

use of photonically based time delays. A typical phased array antenna based on electronic phase shifters would have on the order of a 5% bandwidth. When a bandwidth larger than 5% is attempted with a conventional electronically controlled phased array beamsquint (or beamwander) will occur. This translates into inaccurate and unreliable radar data. A radar system with the advantage of a 50% bandwidth would make it possible to combine the functions of multiple antennas such as radar, communications and electronic warfare, which collectively operate over a large bandwidth into just one array.

2. Theory

2.1 System Description

Conventional phased arrays are steered by electronic phase shifters. Since this steering angle is dependent on frequency the change in angle will vary as the frequency is changed. Because of this, the use of frequency change to steer a beam is limited to only narrowband applications. When wide band applications or large scan angles are attempted with conventional phase shifter based antennas, the steering angle will change. This phenomena is known as beamsquint or beamwander. The equation for beam squint for an ideal electronic phase shifter is given below where f is the center frequency, Δf is the difference frequency and θ is the steering angle.

$$BS = \frac{\Delta f \tan\theta}{f}$$

The concept for this wideband antenna is based on group delays rather than phase combining to form the beam. The wide

bandwidth capability of photonics allows for a frequency independent means to steer the beam. The phased array antenna is designed to be operated in both transmit and receive. Figure 2 depicts the Time Shift Network and the resulting wavefront. For simplicity only one element is shown for each column (level 1). Each column is controlled by one T/R module (level 2). Each T/R module provides a total of 6 bits of

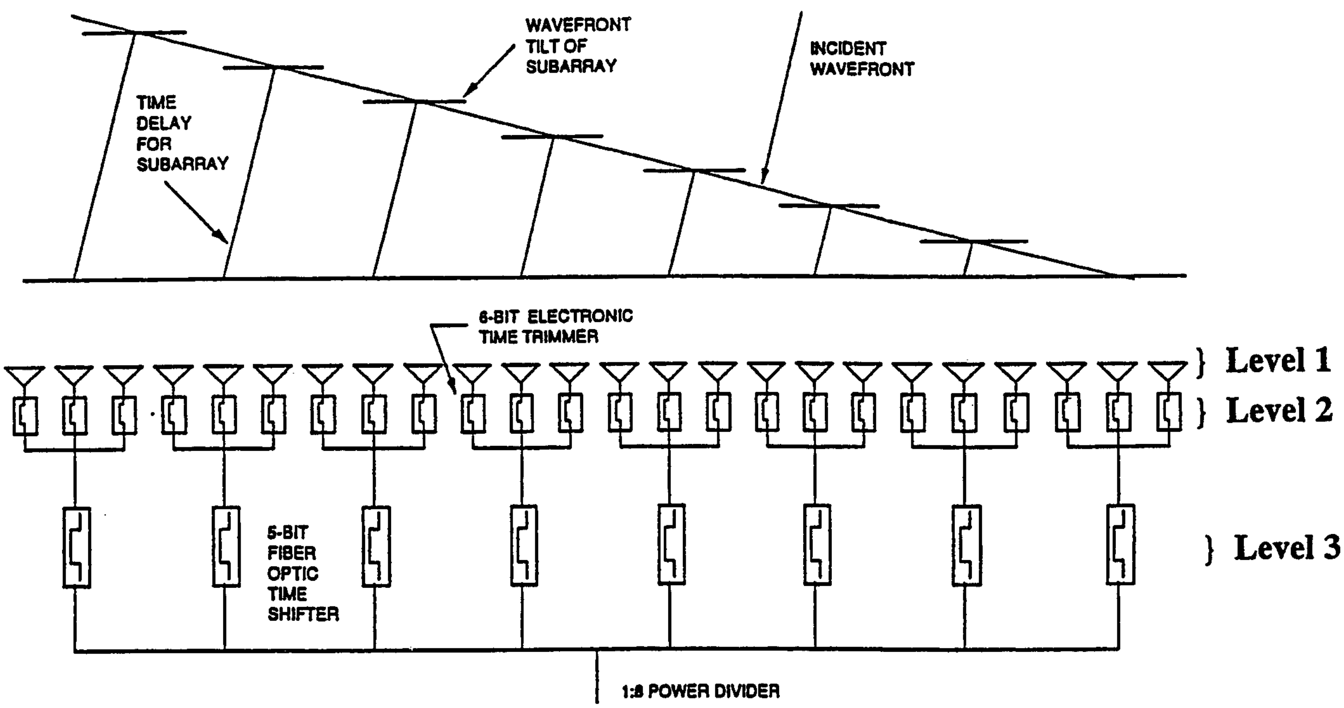

Figure 2. Time Shift Network

electronic time delay. This time delay is for fine tuning on the order of .01 to .5 nanosecond delay. The 5 bit photonic time delay modules (level 3) control each group of 3 T/R modules and 12 antenna elements and constitutes one subarray. The photonic time delay modules provide the course time delay of .25 to 7.75 nanoseconds and are responsible for the large bandwidth of the antenna. There are 32 fiber optic delays associated with each module. The resulting wavefront that is produced scans 60 degrees in each direction.

A system block diagram is shown for the Phased Array Antenna in figure 3. The antenna is completely remoted by a fiber optic link with the exception of AC power. Two single mode fibers provide the RF transmit and receive link and

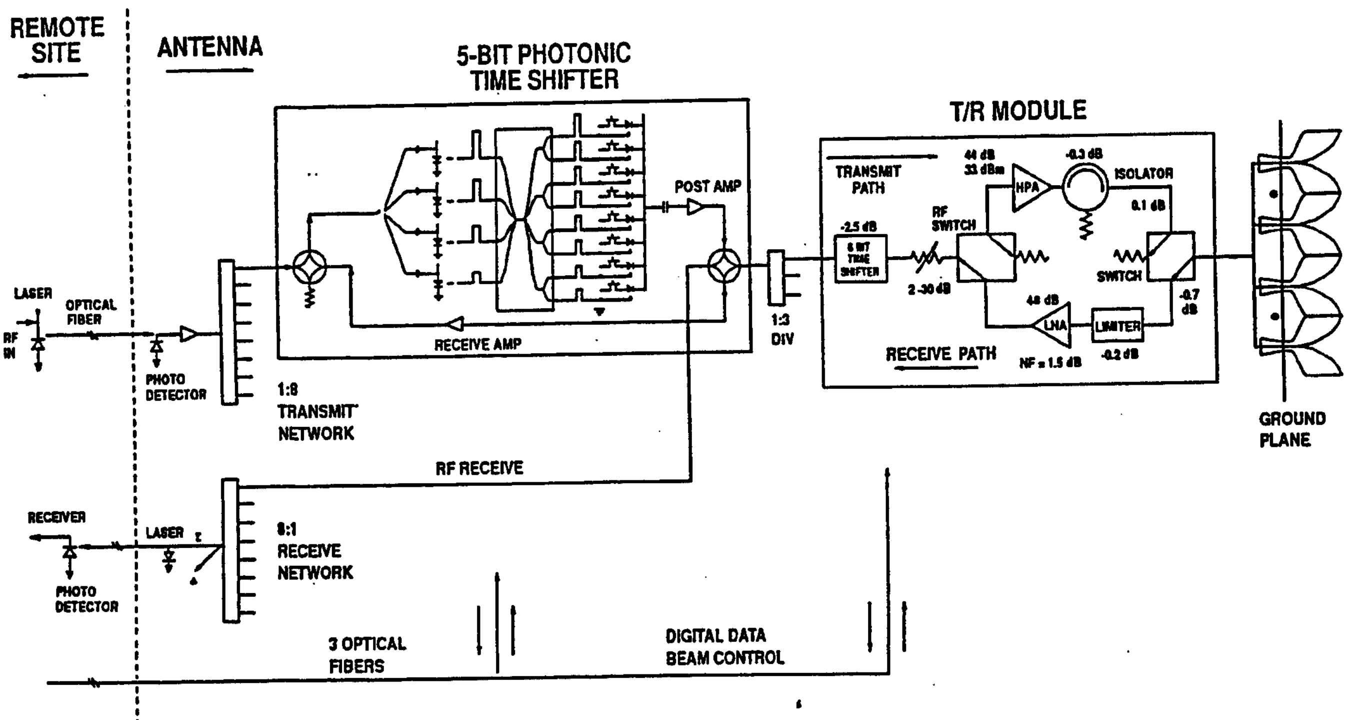

Figure 3. Phased Array System Block Diagram

three multimode fibers provide a digital control link between the antenna and a PC.

When the antenna is in the transmit mode an RF source modulates a laser and the modulated light is transmitted through the 1 Km fiber link to the antenna. The light is then detected, amplified and sent through a 1X8 splitter where it is distributed through the 8, 5 bit photonic time delay modules. Based on the desired steering angle, the beamsteering unit chooses one of 32 paths through each 5 bit photonic time delay module. After that the signal is once again converted to RF and amplified. It then goes through a 1X3 splitter to each of the T/R modules. Each T/R module fine tunes the time delay with a 6 bit time shifter. After amplification the RF signal is radiated by the 24 columns of 4 elements.

When in the receive mode the incoming RF signal is amplified and the fine tune delay is introduced. The signal is then combined with the others from each subarray and the course delay from the photonic time delay modules is added. All 8 subarrarys are then combined and the signal is sent to the receiver.

2.2 Five Bit Photonic Time Delay Modules

The 5 bit Photonic time delay modules are the key components that allow the antenna's large bandwidth. Each of the 8 modules provides the course time delay of .25 to 7.75 nano second delay. The time delay modules are made up of four laser diodes, a 4X8 fiber coupler, and an array of 8 high speed photodetectors. There are 32 different optical paths through each module. Depending on the steering angle chosen

one laser and one detector will be on to give the desired time delay. The time delay module is not a bi-directional device. When the antenna is in the receive mode the signal travels through a transfer switch and then through the device in the same direction as the transmit mode. The conversion loss of the time delay module is 40 dB. A 45 dB post amplifier maintains the desired signal level.

2.3 Beam Steering Unit

The beam steering unit (Figure 4) has a duel role. First it provides for the beam steering function by choosing the fiber paths through the photonic time delay modules and control of the T/R modules and second it provides an error checking capability of the digital control link. Four sets of analog cards provide the drive signals for the antenna steering and 4 sets of digital cards provide the communication link between the PC and the antenna.

When the beam angle is programmed into the computer the required voltages are calculated to steer the beam in the desired direction. The control voltages are directed to the 6 bit time shifters, two T/R switches, and two attenuators located in the T/R modules and also operate the desired laser diodes and FET switches in the photonic delay modules.

The phased array antenna has a built-in test capability which pin-point errors in the BSU. When the PC is first turned on a self test is made which checks the status of all the controller cards of the BSU. A typical error message may be that "there is no 15 volt supply voltage at card 8".

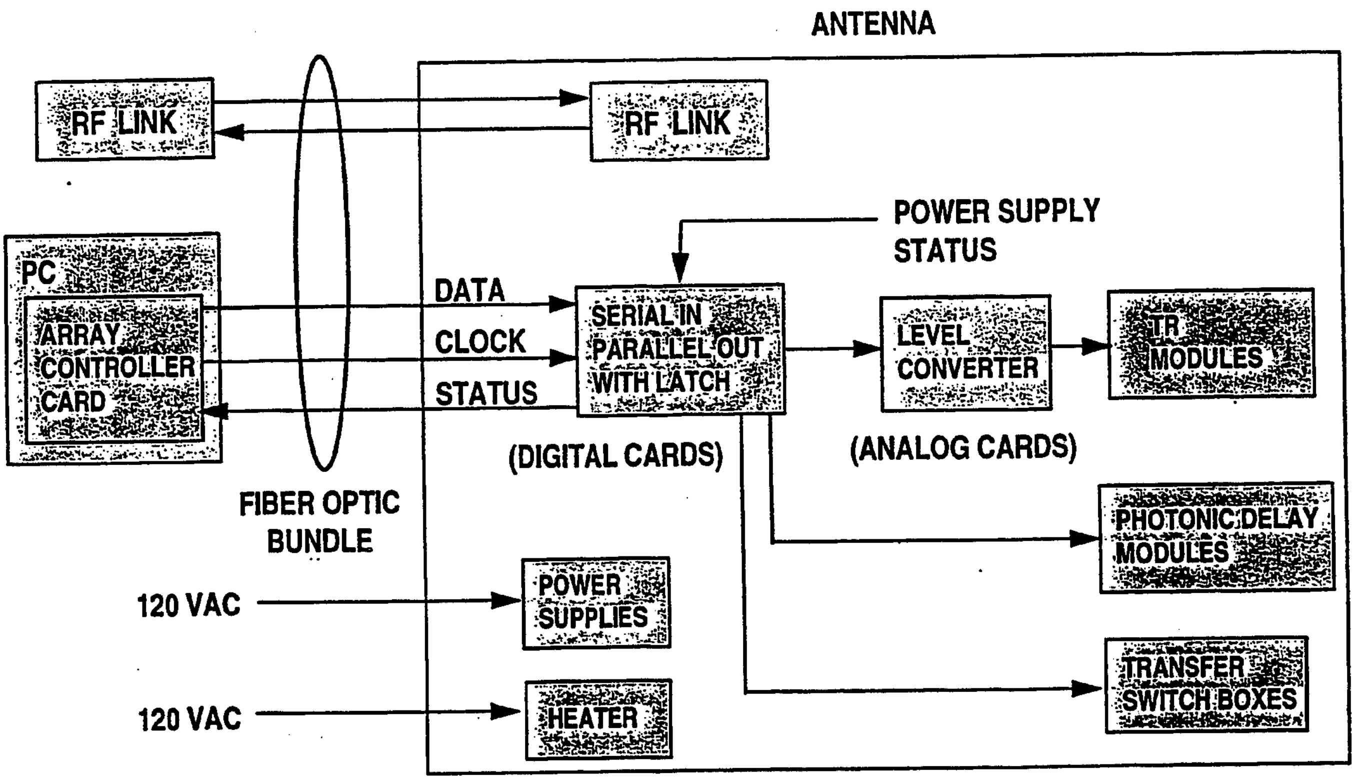

Figure 4. Beam Steering Unit

2.4 Testing Capabilities:

In addition to the built-in test capability of the antenna, an external testing capability is possible using a network analyzer. This capability is called the time domain calibration method. A 2 ns pulse is injected through each column of the array and the return waveforms are then

compared with known data. Figure 5 shows the return for three waveforms. The first waveform represents three T/R modules, the second is three T/R modules delayed, and the third shows that subarray three is not functioning. This testing method was used several times throughout the course of our antenna test to isolate faulty time delay modules.

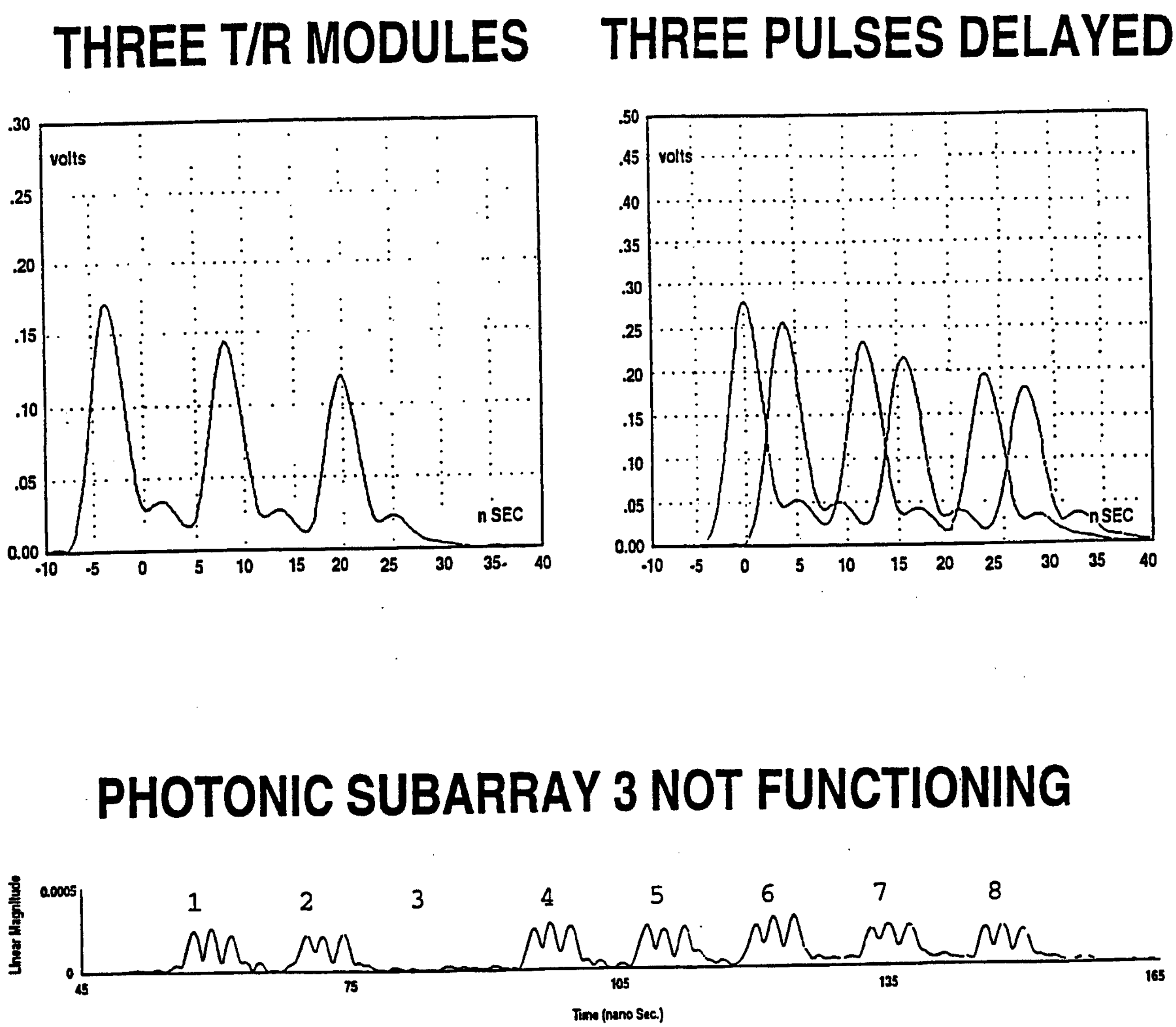

Figure 5. Time Domain Calibration Charts

3. Experiment and Results

The measurements for the antenna test were made at Rome Laboratory's Newport test site. Newport test site is divided in two by Newport/Schyler road. The Irish Hill site is on the east side and the Tanner Hill site is on the west. The June/July 95 tests were on Irish Hill and the May/October 96 tests were held on Tanner Hill. The test ranges for each site are very similar. The major difference between the sites is the distance between the antenna and the Transmit/Receive dish. The Irish hill site measures 1800 feet between the antenna and dish while the Tanner Hill Site measures 674 feet. To prevent duplication I will discuss just the Range instrumentation for the Tanner Hill Site.

The Range instrumentation used in this experiment is shown in figure 6. The Phased Array Antenna was mounted on a 40 foot tower. A standard gain horn antenna was mounted 180 degrees from the Phased Array Antenna to establish a reference. A Heurikon HPE/05R computer located in the base of the tower was used as the real time acquisition system. A transmit/receive dish was located 30 feet off of the ground, 674 feet down range from the Phased Array Antenna. The antenna was controlled and data was taken from the Operations room, adjacent to the Transmit/Receive dish. Remoting was accomplished using a 1 Km length of fiber. A DEC work station located in the operations room was used to process and record the data.

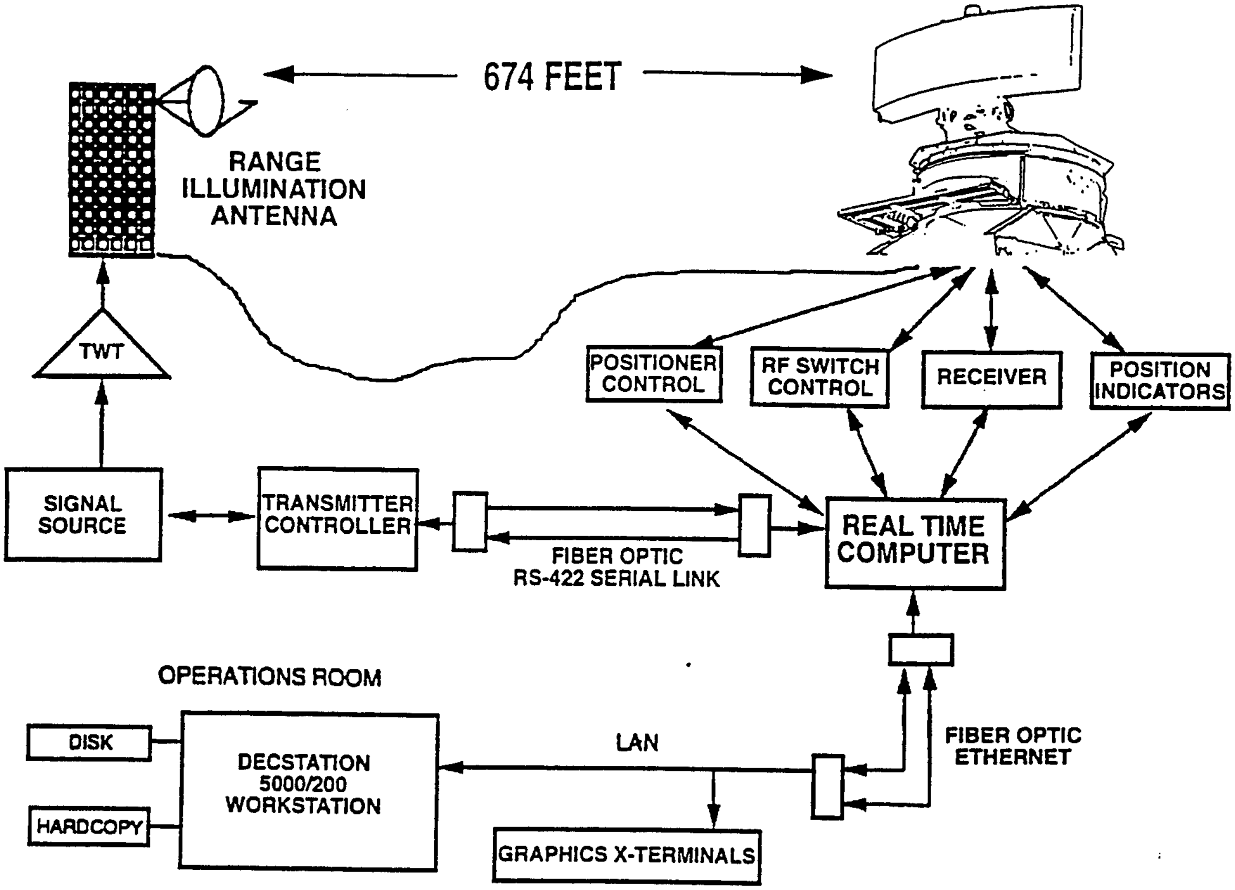

Figure 6. Range Instrumentation

3.1 Irish Hill Result

Three major points were demonstrated during this experiment, the first of which is wide bandwidth capability by the use of photonics. In figure 7, three beam patterns at 1125, 1250 and 1400 MHz at a scan angle of 60 degrees is shown. The actual steering angle of the three beams is approximately; 60 deg. at 1125 MHz , 60 deg. at 1250 MHz, and 63 deg. at 1400 Mhz. By applying the formula for beamsquint given on page 2, the expected beamsquint for an ideal electronically controlled phased array antenna would be; 60 deg. at 1125 MHz ,71.02 deg. at 1250 MHz, and 84.26 deg. at 1400 Mhz. This yields an improvement of 11.02 deg. for 1250 Mhz and 21.26 deg. for 1400 MHz. By using photonic time delays in place of electronic phase shifters, beam squint was minimized for wide bandwidth applications.

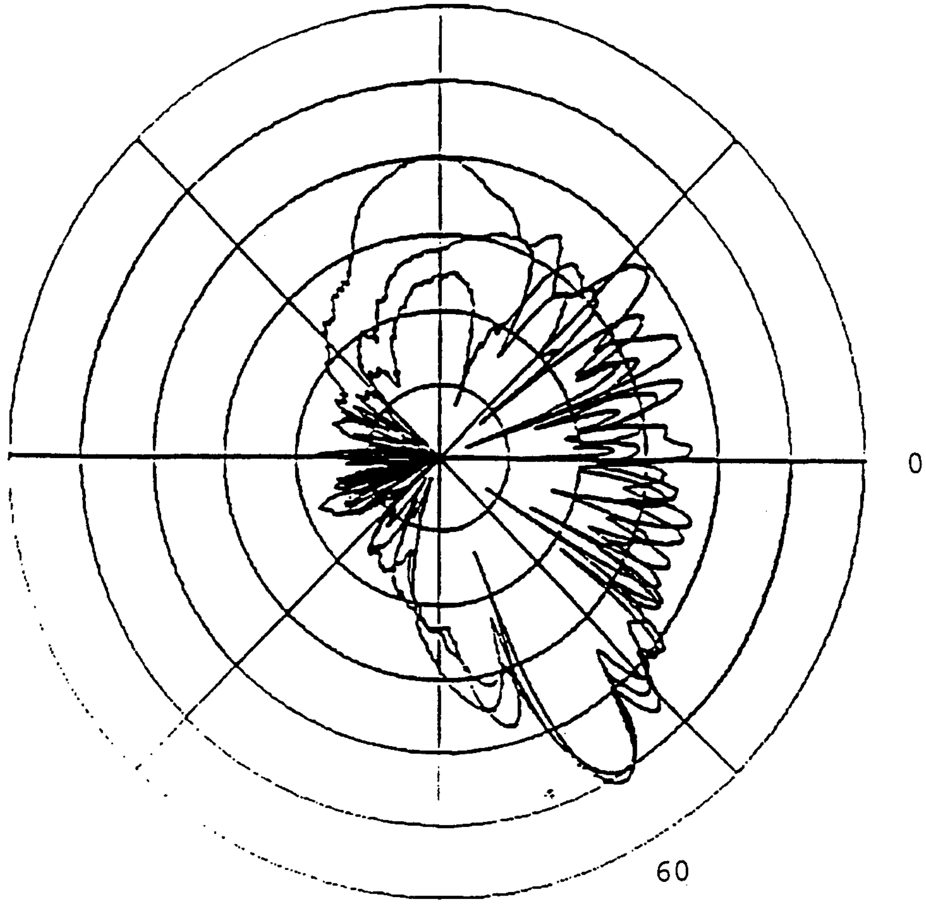

Figure 7. 3 Beams at 60 degrees

Second, during the initial start-up and test of the phased array antenna the built-in test feature of the BSU was put into use. When the initial commands were entered into the PC to check the errors of the BSU, errors were displayed in modules 3 and 6. Upon examination of these modules it was noticed that the bus connectors which attach to the modules had come loose during shipping. Once the connectors were firmly in place the BSU checked out error free. With out the built-in test capability one could have spent hours trying to locate a problem instead of minutes.

A lightning storm which occurred over the 4th of July weekend helped demonstrate the third point. The results of the

initial test before the lightning storm were very good. Figure 8 shows a beam pattern recorded before the lightning strike and figure 9 shows a beam pattern recorded after the lightning. The pattern in figure 8 is evenly distributed with side lobes down about 12 dB. The pattern in figure 9 is distorted with little gain. There clearly was a problem. With the use of the HP8510 network analyzer and the time domain calibration method discussed in section 2.4, the problem was isolated down to the component level in three of the photonic delay modules. Using the time domain calibration method pulses were injected into the transmit and receive paths of the array. By examining the returned data it was determined that there were multiple FET's on in three photonic modules. When multiple FET's are on several optical paths are chosen through the 5 bit photonic time delay modules causing inaccurate data. The modules were removed and sent back to Hughes for repair.

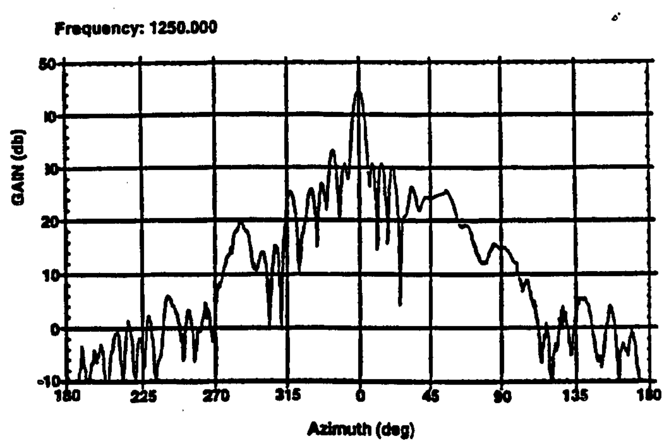

Fig 8. Pattern before storm

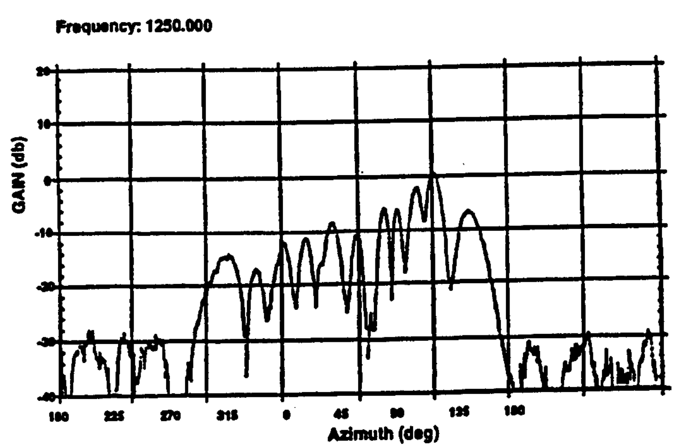

Fig 9. Pattern after storm

3.2 Tanner Hill Results

The antenna was re-assembled after repairs were made on several of the photonic modules from the previous year. The initial beam patterns that were taken in the summer were reasonable. Side lobes were down about 10 dB as expected. The results of 12 dB main lobe above sidelobes from the previous years results were exceptional. Acceptance test data from Hughes were in the 10 dB range. One of these patterns is shown in figure 10. The next day pattern irregularities began to show up. The amplitude of the main beam was very close to the sidelobes (figure 11). One or more of the photonic delay modules was the probable cause.

Once again the time calibration method was used to trouble shoot the antenna. After analysis it was determined three of the time delay modules and a bus card were faulty. Two of the modules were ones that had been repaired the Previous year. The components were removed and sent back for repair. Further testing was postponed till fall

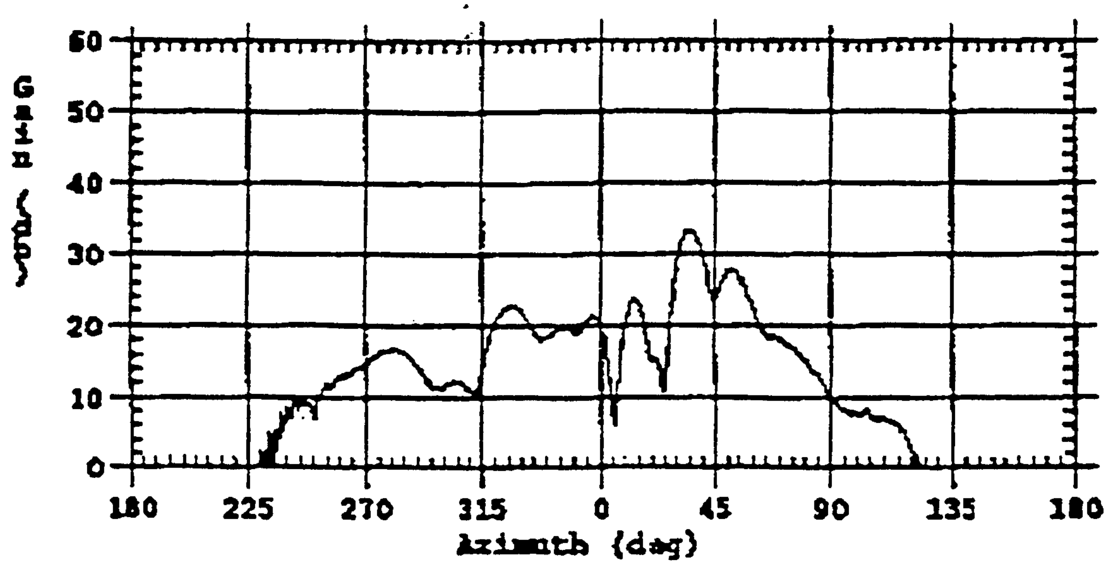

Figure 10. Initial Pattern Summer 96

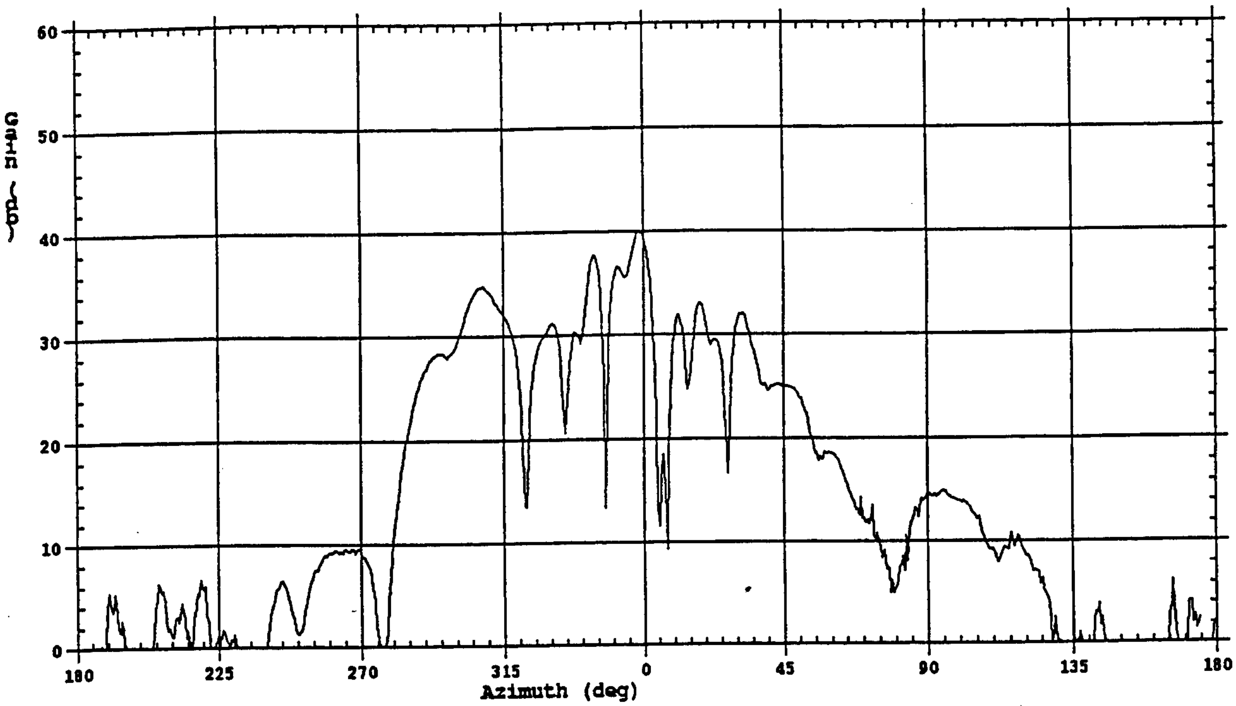

Figure 11. Distorted Pattern Summer 96

When testing resumed in the fall, a repeat of results from the spring occurred. Results were very good for the first day but once again the patterns deteriorated. The network analyzer was no longer available so we used another approach for diagnostics.

The phased array antenna has the capability of individually turning each T/R module on or off. By turning the T/R modules on in groups of three each of the subarray patterns can be examined individually. The subarray patterns shown in figure 12 are uniform and evenly distributed. These patterns indicate that the subarray components are functioning properly. The patterns in figure 13 are distorted

and the amplitude is attenuated. This indicates problems with those particular subarrays. By looking at the subarray patterns we can get a general idea as to which subarrays are functioning properly and which are not, but it does not give the details that the time domain calibration method does.

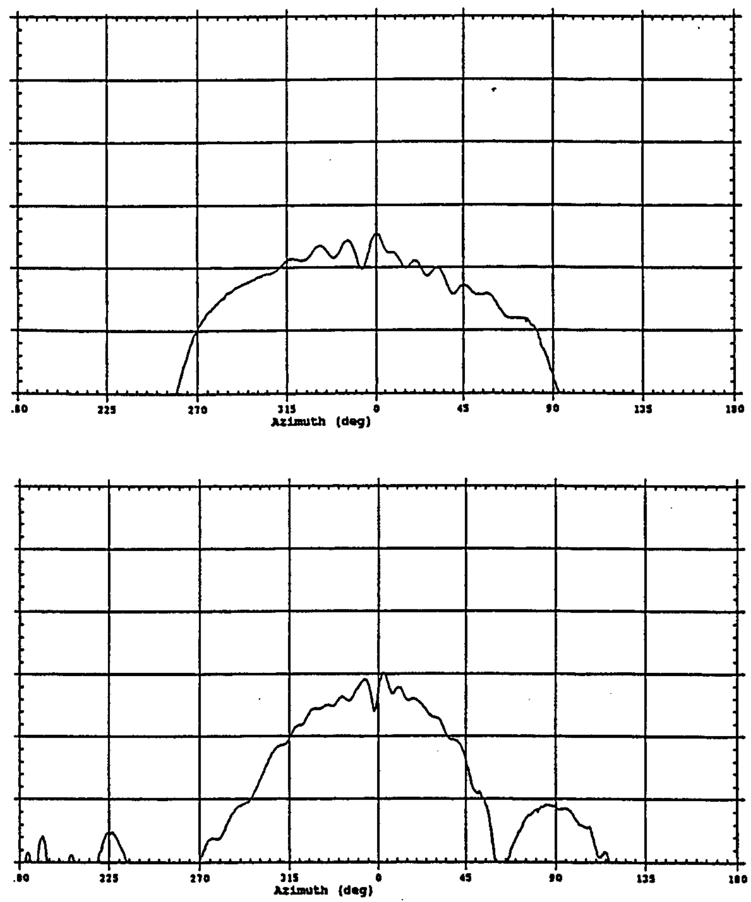

Figure 12. Normal Subarray Patterns

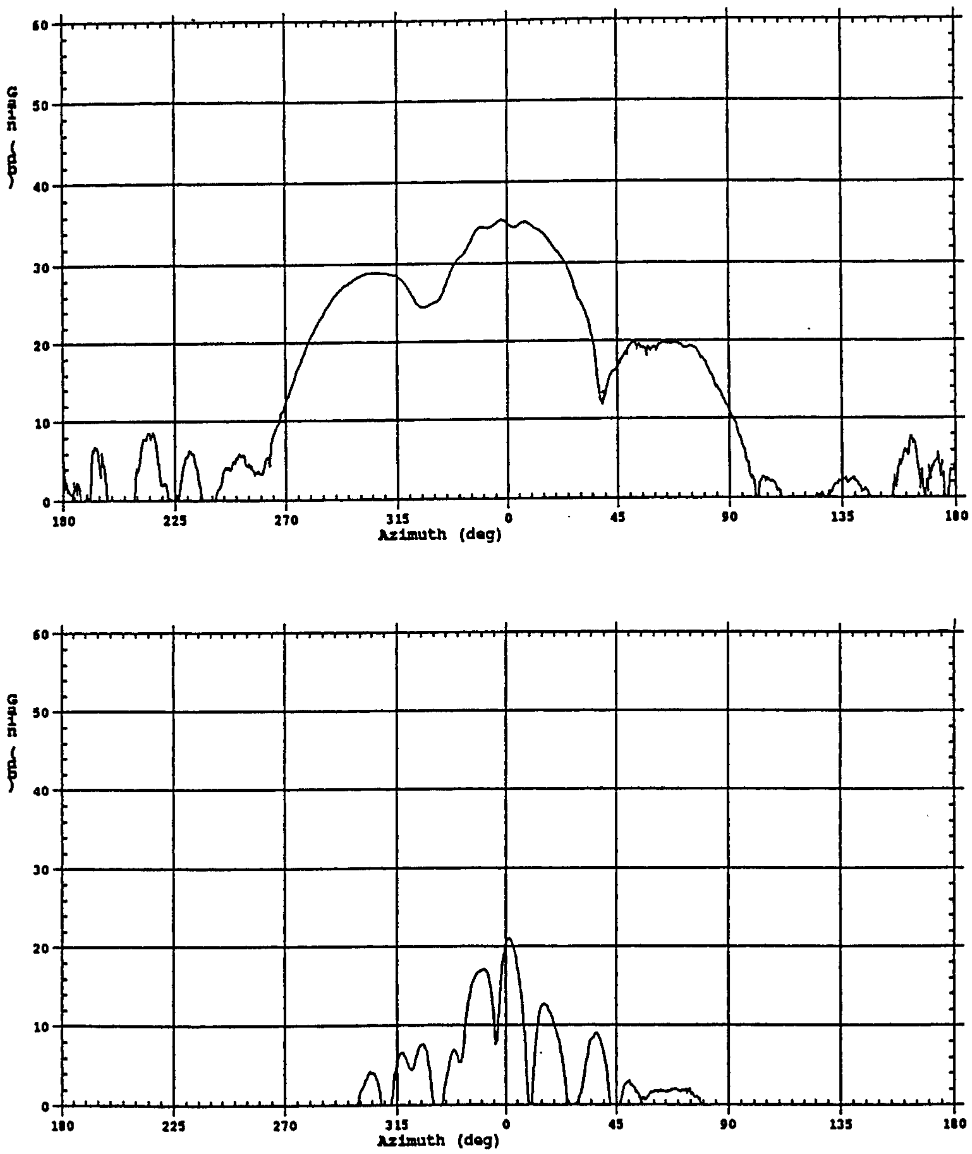

Figure 13. Distorted Subarray Patterns

4. Conclusion

The basic concepts of the Optically Controlled Phased Array Antenna have been proven. The wideband capabilities by the use of true time delay far exceed the capabilities of an electronically controlled phased array antenna. Improvements in beamsquint ranged from 11.02 degrees to 21.26 degrees over a bandwidth of 1125 MHz to 1400 MHz. These improvements were at a steering angle of 60 degrees, the largest scan angle, which experienced the largest beamsquint. The external testing capability also worked very well. Problems were correctly identified down to the component level. Reliability problems hampered our tests of the antenna. Initially the lightning storm was blamed for the problem, but, further tests proved the antenna had reliability problems. The problem was the reliability of the FET's in the 5 bit photonic time delay modules. For an operational system these reliability issues would have to be thoroughly addressed. Here we had only a proof of concept for the photonic beamformer. Due to funding constraints there are no testing plans in the immediate future.

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3) "Antenna Theory and Design", Warren L. Stutzman, Gary A. Thiele, John Wiley & Sons 1981.

4) "Air Force Measurements of an Optically Controlled Phased Array Antenna", David A. Garafalo, Norman P. Bernstein, DOD Photonics '96, March 1996

5) "Characterization of an Optically Controlled Phased Array Antenna", David A. Garafalo, SPIE April 1997

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Appendices A:

Phased Array Control Menu

Antenna

<1> Toggle between Transmit/Receive

<2> Set beam angle

<3> Self Test

<4> Send command to array

<5> Set all F/O & T/R delays

<6> Toggle selected T/R module attenuators on/off

<7> select waveforms from analyzer

<8> Diagnostics

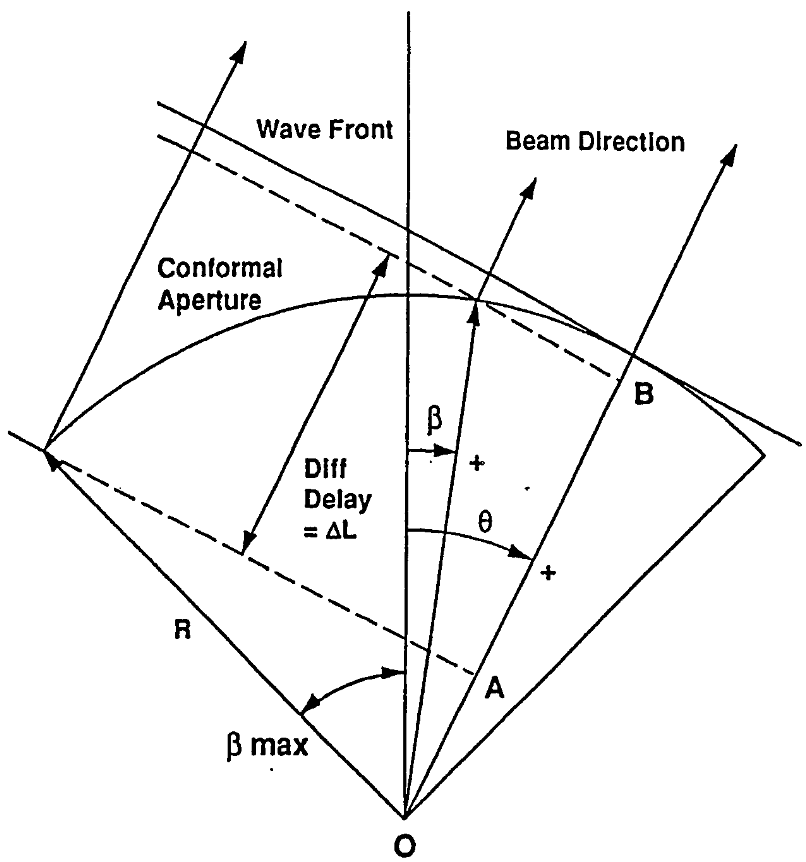
<9> Cycle through 32 photonic delay states & download analyzer

<12> Down load analyzer data

<20> exit

Appendices B:

Conformal Array Beam Steering



θ = Scan Angle

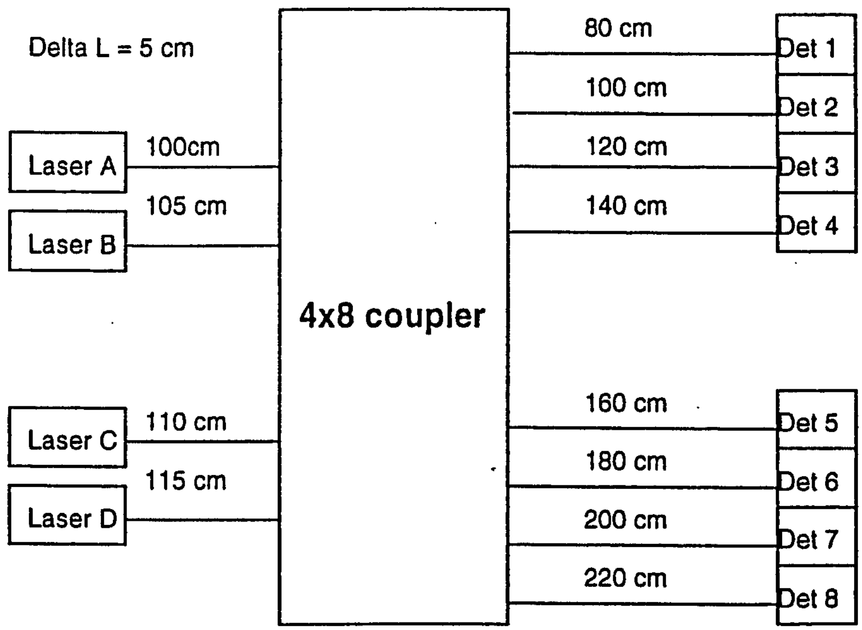
β = Element Location

$$\text{Diff Delay} = \underline{OB} - \underline{OA} = \Delta L$$

$$\Delta L = R\ [\ \cos(\theta - \beta) - \cos\ (\ |\theta| + |\beta|\ \text{max})\ ]$$

Appendices C:

True Time Delays



Delta Delay Time, ns

Det	Lasers			
	#A	#B	#C	#D
1	0	0.25	0.5	0.75
2	1	1.25	1.5	1.75
3	2	2.25	2.5	2.75
4	3	3.25	3.5	3.75
5	4	4.25	4.5	4.75
6	5	5.25	5.5	5.75
7	6	6.25	6.5	6.75
8	7	7.25	7.5	7.75